Structural System in Architecture
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Lecture – 25
Space Frame Structures

Welcome to the NPTEL online certification course on Structural Systems in Architecture. This is module 5, Truss and Space Frames; and this is the last lecture on this module. In serial this is lecture number 25. The topic of today's lecture is "Space Frame Structures".

The concepts to be covered under this lecture are:

- Introduction.
- Formation of Space-Frame Structures.
- Support System of Space-Frame Structures.
- Classification of Space-Frame Structures.
- Advantages of Space-Frame Structures.
- Application of Space-Frame in Architecture.

First, we will start the introduction of the Space-Frame, then we will go to formation of the Space-Frame structures, how it is going to form, what is the typical geometric pattern of formations of the structures. Then we will discuss the support system of space frame structure, which is also very important. Where we will try to understand how the Space-Frames can be supported. After that we will see the classification of Space-Frames; and then advantages of Space-Frame structures and finally, we will see some applications of Space-Frame structures in Architecture.

The intended learning objectives are to:

- Define and understand Structural Configuration of Space Frame Structure.
- Illustrate the geometric formation of Space Frame Structure.
- Know on Applications of Space Frame Structures in Architecture.

So, we will define and try to understand the structural configuration of Space-Frames. The configuration of Space-Frame structure is one of the important criteria for selection and application point of view, like how it can be applied if you know the total area and if you know what will be the type of activities in that space, the you have to come back to the structural configuration of that particular type of Space-Frame. Of course, there are other criterias are also involved, like cost,

material availability etc. Next, we will illustrate some of the geometric formation of the Space-Frame under the classification; and we will also discuss on application of Space-Frames in Architecture.

Space-Frame are three-dimensional Truss system consists of Top and Bottom surface grids; and they are mutually connected to each other by diagonal members or the links. The whole system of three-dimensional network of struts and bars are connected via nodes. Refer Figure-1.

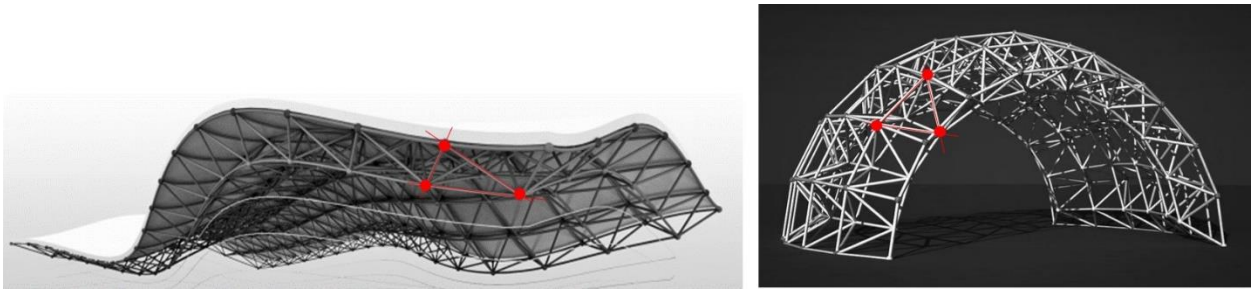

Figure 1 : three-dimensional Truss system or the Space-Frames

These two images in Figure-1 signifies the typical types of the Space-Frame structures that can be thought of. It is three dimensional, and inclination of each elements are in a three-dimensional plane. We can also say that it is one of the prominent vector active structure. In Figure-1, if you see the images carefully then you will notice that there are small connection points, the red dots, they are the nodes; and they are connected with some small, small straight members, the red straight lines, and they are the links. In the images, those links seem to be of very lightweight.

Some of the typical characteristics of Space-Frame are:

- A Space-Frame or Space Structure is like a three-dimensional Truss system.
- The lightweight rigid links are interlocked to provide a geometric pattern.
- Tetrahedron, Cube and Octahedron are the commonly used geometrical forms that creates the Space-Frame.
- It can be used to cover large areas with fewer column supports.
- These structures are strong because of the following:
    - Inherent rigidity of the triangle.
    - The external load is distributed over an area and control over the compressive and tensile forces

The load distribution in Space-Frames are very smooth and uniform all over the structural systems. So, this has wonderful applications in the Airports, stadiums and other large span structures.

In Figure-2, there are some links, and they are in two-dimensional plane; and there are seven links and tied at different points. But there are some open ends as well. Anyway, can you guess what can be that element? Remember, this is a two-dimensional Truss and the links are in one plane.

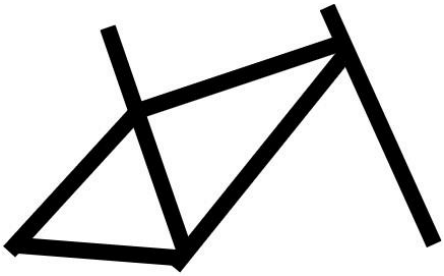

Figure 2 : two-dimensional Truss with seven links

So, this can be the part of a bicycle. Right? Refer Figure-3. So, a by cycle made of those links. As this is two-dimensional, no link is extended outward except the handle of the bicycle which is missing in Figure-2.

Figure 3 : a bicycle with two-dimensional truss

In Figure-4, this is a Space Truss or three-dimensional Truss. Then, what can be the purpose of this? This is for automobile car.

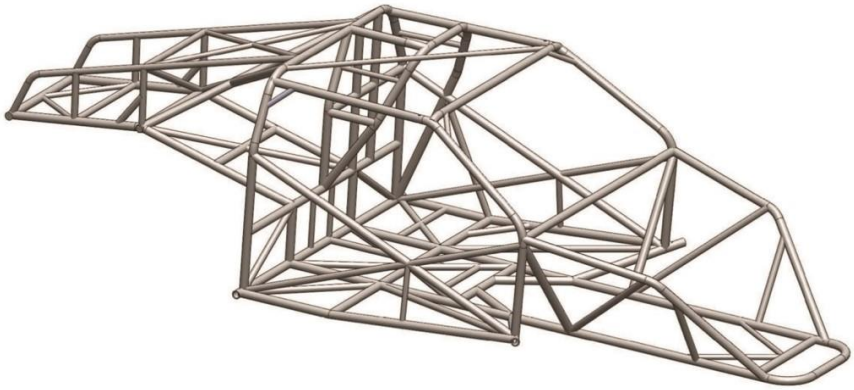

Figure 4 : a three-dimensional Truss

So, if you see the skeleton of a car which is three dimensional in nature with links and nodes. Those links and nodes creates the stability and the strength of the item. So that is how it is different from a bicycle. In similar way we can compare the two-dimensional Truss and a Space-Frame.

Next, let us go to the formation of Space-Frame structures, which is very, very important. Here, I have given some small units or modules that are used in Space-Frames. These modules can be created by cubes or may be the Tetrahedron or the Octahedron etc. as shown in Figure-5.

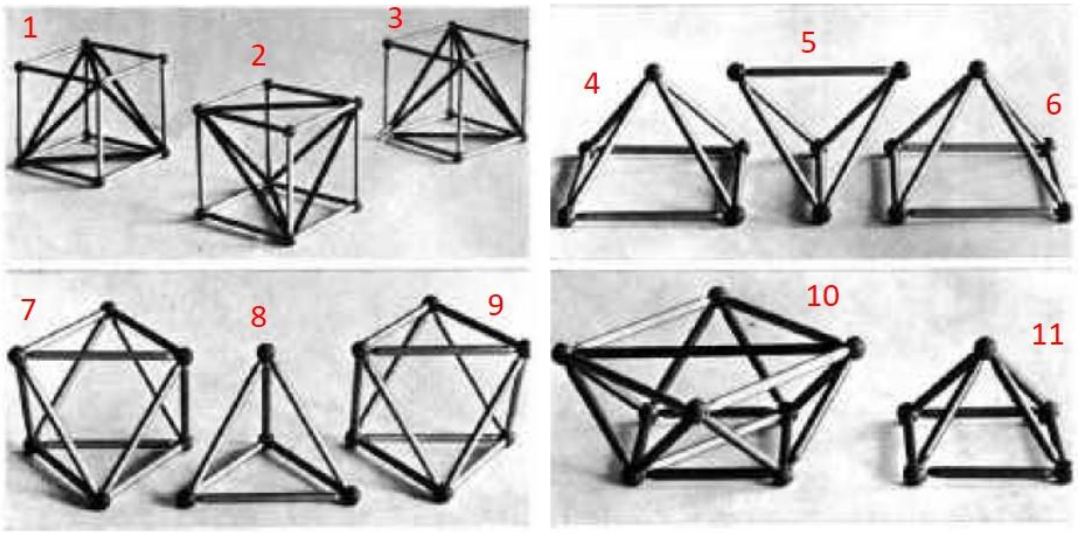

Figure 5 : the small units or modules used in Space-Frames

Please remember that these forms can be created by links and nodes. Refer Figure-6.

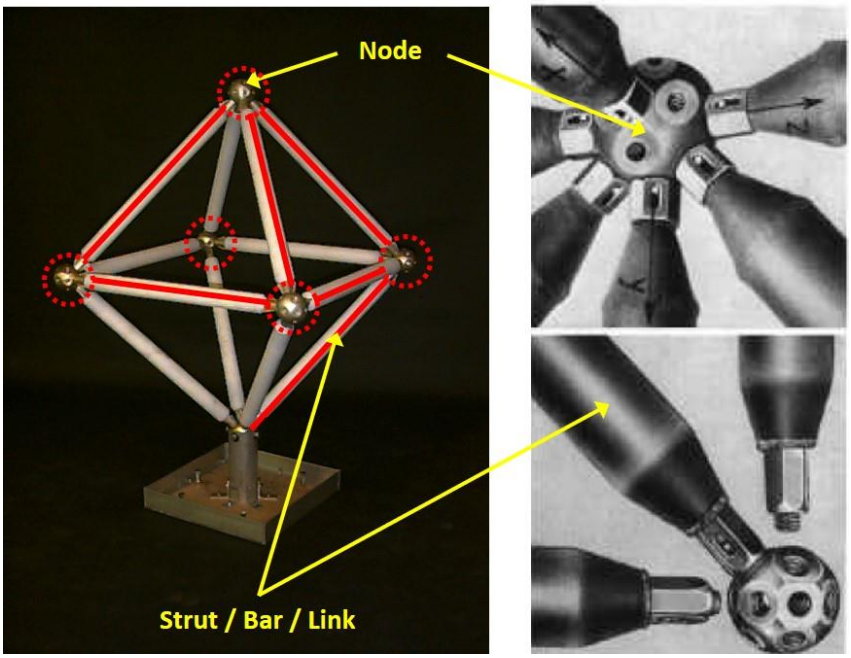

Figure 6 : links and nodes in a Space-Frame unit

Then what is the function of a link? The function of a link is to transmit the load from one point to the other point, so it will transmit the load from the one node to the other. These transmissions will result into either compressive or tensile forces on the links, depending upon the orientation and nature of loads. From the Figure-6, it is clear that the nodes are like a ball. The nodes and links are mainly made of aluminium or steel. So, this one of the simplest forms of the Space-Frame shown in Figure-6.

Now, one such module can be repeated in the various points, and when you repeat those various points, then it maybe in one layer or may be in multi-layers. In Figure-7, it is a very simple Space-Frame block. In case A, there are four supports at the four corners; and on that there is a Space-Frame. So, one maybe the lower grid, and one maybe the upper grid. And depending upon the geometry or configuration of the modules, which may be small triangular light module or may be a with heavy geometry, we have to decide the distance between the supports.

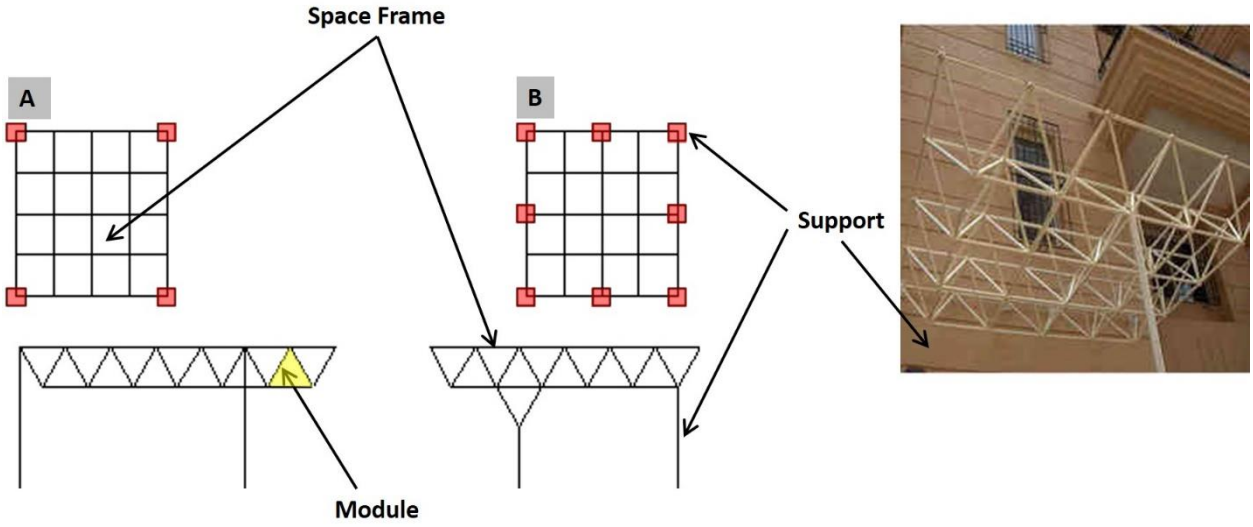

Figure 7 : Space-Frames

If it is a light module, we can have more distance in between the supports and if it is a heavy geometry the distance between the supports will be reduced. If you see in case B, the supports are nearer to each other compared to case A. That means case B with a heavy geometry. Hence, we can say that, based on the geometry of the modules, you have to decide should be de the distance between the supports. The support system can be the column or wall etc. If you see in Figure-5, where the modules are numbered, there number 8 and 5 are very light modules whereas, number 2 and 9 are very congested or a compacted module. The compacted module can go for larger span

and the light models can have a smaller span. Smaller span in general because the number of elements are less in the less congested modules.

Now, if we see the details of a single unit of Space-Frame Module, let us consider a module like as it is shown in Figure-8, then there are three layers, actually two layers and there is a binding element. This red color topmost part is called the Top Chord. This Top Chord may be rectangular, or squarish, or may be triangular, out of all these, squares and the triangles are very common and popular type of formation. So, this Top Chords are connected by those small balls or the nodes.

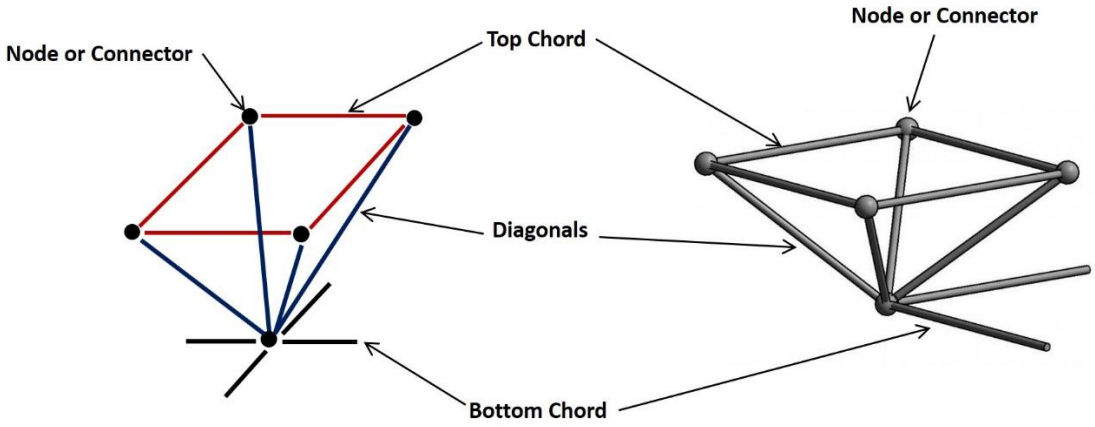

Figure 8 : top chord, bottom chord and diagonals of a Space-Frame

There are Bottom Chords also. The diagonals connect the Top Chord and the Bottom chord. The Bottom Chords sometimes follow the Top Chord; that means if the Top Chords are squarish or rectangular or triangular Bottom Chord also follows the same pattern; or sometimes Bottom Chord is little lighter with respect to the Top Chord. But there are maybe smaller variations in the Bottom Chord. However, there has to be a Bottom Chord and a Top Chord which will be connected by the diagonals. Refer Figure-8 for details.

Now, if you see from major classification point of view then Space-Frames have two types, one is linear, beam like Space-Frame; and other is three-dimensional Space-Frame.

So instead you are providing any kind of a solid beam, solid steel beam or maybe a solid Truss, you can go with a 2-dimensional Truss or those kind of the Space-Frame. In Figure-9, these are linear, beam like Truss. In case A, it is a Space-Frame, with three Trusses, where two Trusses are inclined and one Truss is the flat in the bottom. The second one, case B, there are 4 such Trusses, two Trusses are parallel and vertical and other two Trusses are parallel, horizontal and flat. Hence, in this way also you can create a linear Space-Frame which is very much authentic, whighly

applicable and much practiced in Architecture or in our structural systems of buildings, especially for airports, railway stations.

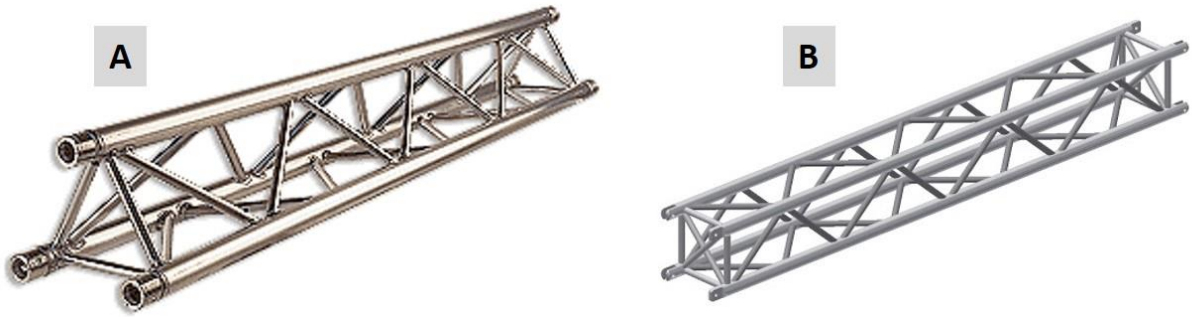

Figure 9 : linear beam like Space-Frame

In this type of linear beam like Space-Frame, we remove the heavy beams and create lighter structure with a higher depth; so that we have the higher depth for moment of inertia to get better stability. As you know, if you create a higher distribution of materials then moment of inertia will definitely increase and when it will increase, it will give you better stability or better safety against the bending moment and other forces.

Whereas, the second type of Space-Frame is three-dimensional in nature. It does not have the linearity. It has a spreading over a particular area with those Bottom Chord, Top Chord and the connecting diagonals.

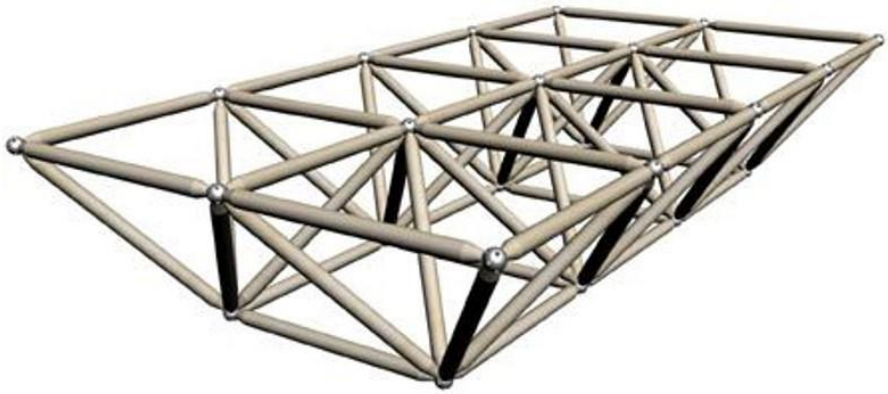

Figure 10 : three-dimensional Space-Frame

Next, we will see the types of connections in a Space-Frame. We have already talked about the nodes and the links. The links may be steel pipe or maybe aluminium links, which may be solid or hollow in nature. There are n number of varieties of material and types. But the connectivity of links to node or these node connections are of three types.

i. Welded connection

ii. Bolted connection

iii. Threaded connection

Figure 11 : welded connection

First, we will see the welded connection. Here, we just weld it; the members can be weld together. It looks like as shown in Figure-10. There is no question of any kind of a deformation. If there is a we apply a slight dynamic kind of loads on the top of the frame, it will not give any displacement or it will not deform. So, we can say that it is a very rigid system. For example, the body of a car, body of an aircraft etc. are first made of Space-Frame structures with welded connections; and then we put the other materials. For many buildings we go for welded connections, because it is cheaper and easy to erect. If it is a smaller area, then I would definitely go with welded connections. The second one is the bolted connection. When there are angles like T sections, we go for bolted connections. We can create Space-Frames by virtue of the angle T or such sections. It is very difficult bolting the circular pipes or members. But, even if it is difficult, with circular sections we can create Space-Frames; with welded connection we can attach a Gusset plate and then we can bolt the sections to it, in order to generate the Space-Frame.

Figure 12 : bolted connection

Nowadays, there are very high strain friction grips bolts are available which can provide really good stability. The bolts give you little bit of relaxation or flexibility on movements. It is not exactly100% rigid like the welded connections.

The third one is the threaded connection. This is very popular and very easy to install. The threaded connections have bolls as nodes, with required number of holes in it, to hold the links. So, the holes also control the direction of the links. The number of holes on the ball depends upon the design of the module. If it is a triangular unit, it will be different, if it is a square the design of holes in the ball will be different, if it is a tetrahedron you have to go for different design of the ball with different number of holes. Because, with change in the module, triable, or square, or cube, or tetrahedron, the number of links in the module will be different. So, with respect to that the ball will be oh different design. Refer Figure-13.

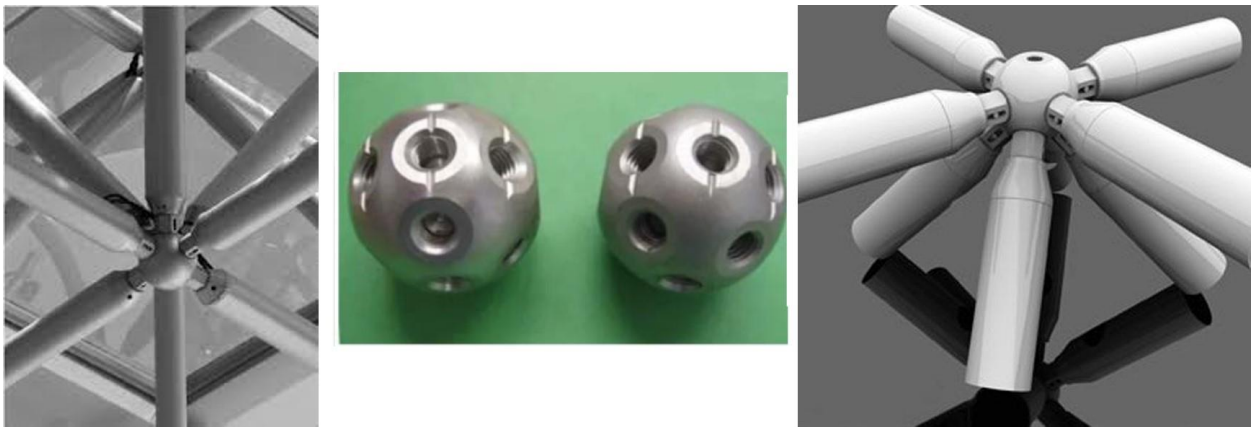

Figure 13 : threaded connection

So, as it is threaded, this gives you some degrees of flexibility, or we can say that this type of connection gives you much better flexibility with respect to the bolted or welded connections.

So next is the support system of the Space-Frame. How the support can be thought of? The support system of the Space-Frame can be of:

- Top Chord Support.
- Bottom Chord Support.
- Four Point Support.
- Frame Capital Support.
- Interior Wall Support.
- Exterior Wall Support.

The Top Chord Support, as the its name suggest or name explains that it is supported on the Top Chord of the Space-Frame structure. Similarly, next is Bottom Chord Support, and the support rests on the Bottom Chord of Space-Frame structure. Refer Figure-14.

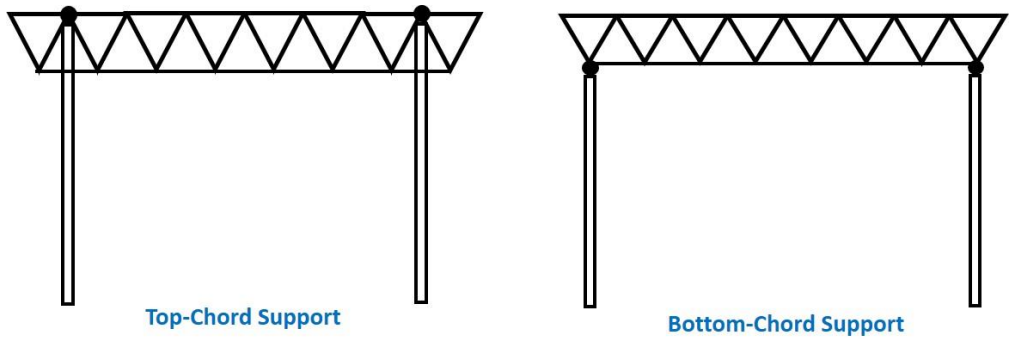

Figure 14 : Top Chord and Bottom Chord supports

Sometimes, it can be with wide supports, we give Four Point Support. In Four Point Support we increase the bearing area. So, suppose you have a lot of expanded portions of the building that has to be covered by the Space-Frame; and you want to reduce the number of columns. But reducing number of columns may not be a problem; because the column can have the enormous strength, and can take the load if we increase the bearing area as shown if Figure-15. If we do not do that and put simple columns at wider distance, then load or the stress concentration may occur if you just direct with the Top Chord or directly put it on the Bottom Chord. So instead of that we go for extended plate on top of column support. So, Four Point, panel may be created below the Space-Frame and that can be supported by columns.

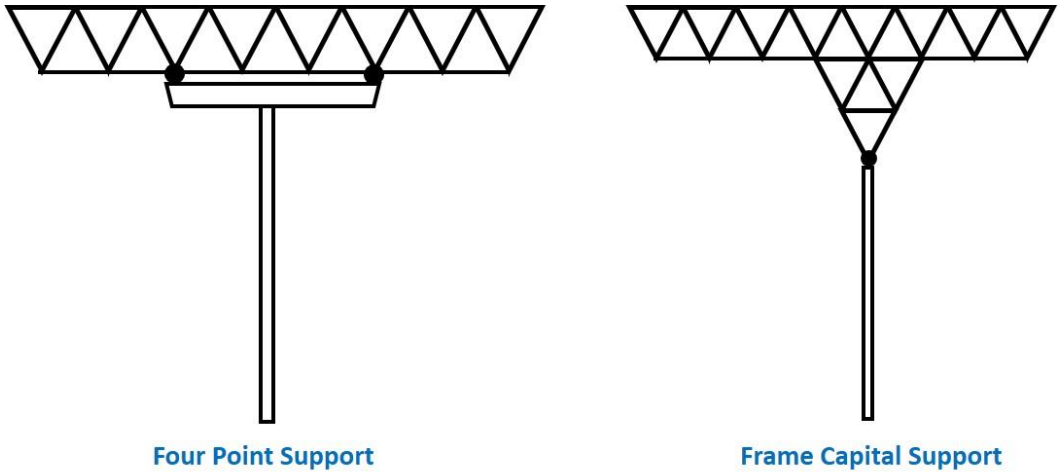

Figure 15 : four-point support and frame capital support

Sometimes it may be a gradual capital type of support. Where you create two or three layers of the module, gradually narrowing towards the column top; then gradually the load can be transferred to the column; and we can achieve good bearing from such supports.

Finally, we can have the walls as supports, so there will be a series of support, as shown in Figure-16. These can be metal support, which rests on the interior wall. Sometimes it can also be the exterior walls.

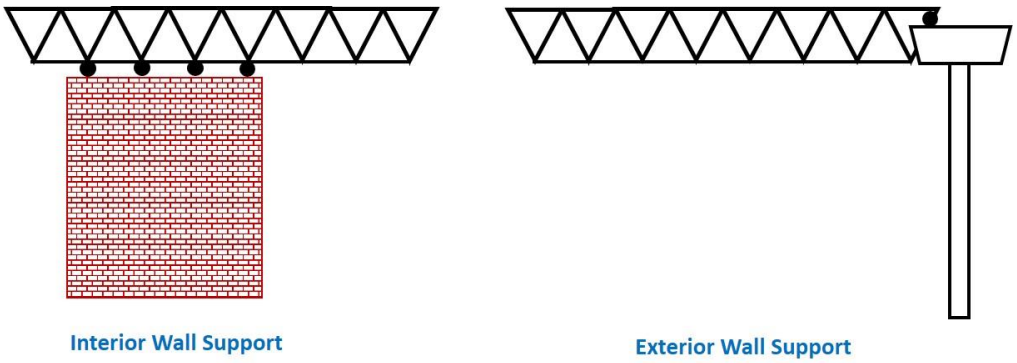

Figure 16 : interior wall support and exterior wall support

So, the extended portion of the exterior wall can also be used as the support of a Space-Frame structure. But all these depends upon the different situation of the building and how the Space-Frame that needs the support. You need to thought about the supports depending upon the layout of the building and such other parameters of the building. And, based on that you have to select the different type of support system.

Now, we will see about the span, the depth, the roof slope and ratio of overhangs in a Space-Frame.

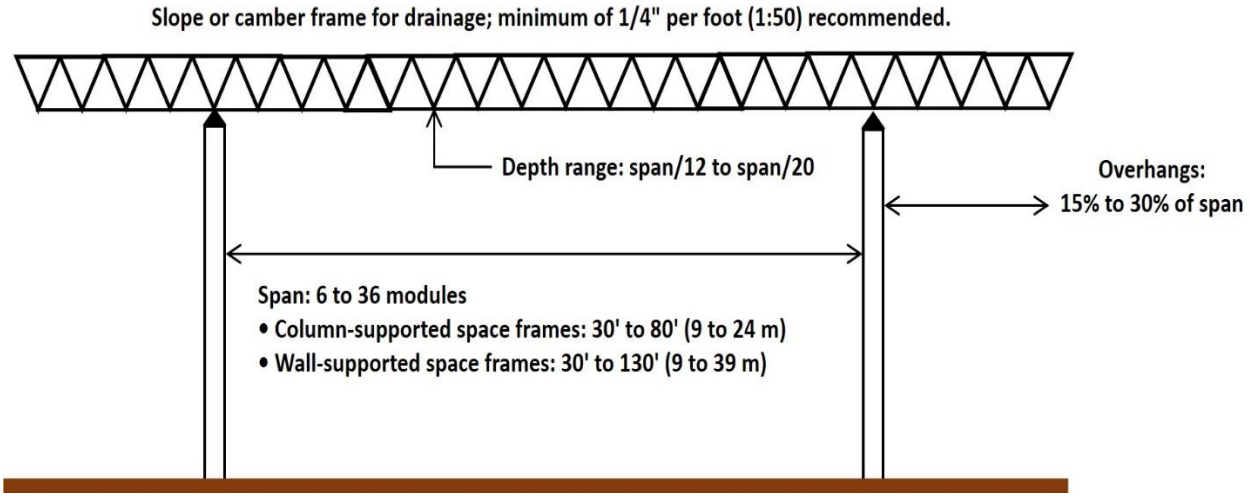

Figure 17 : some details of a Space-Frame

The span of a Space-Frame continue for 6 to 36 modules. For the column supports it is almost 30 to 80 meters. That means the center-to-center distance of the columns can be 9 to 24 meters. In case of the wall supported frames, it may go further high. It can be of 30 feet to 130 feet which is almost 9 to 39 meters. Therefore, we have to see that the number of modules and distance between the supports changes depending upon different types of support system.

The depth of Space-Frame ranges from, span by 12, to span by 20. Suppose if the span is 24 meters then depth can be 24/12=20; or 24/20=1.2 or 1.8 etc. Then comes the slope at the top. The top portion either it can be camber for drainage. The slope or camber for drainage should be minimum of 1/4 inch per foot or maybe 1 is to 50 is the recommended slope. Sometimes we may go little higher, maybe 1 :75, or 1:80 also. In some cases, there will be extended roofs. The extended roof or the overhanging part can go up to 15 to 25% of span of the Space-Frame. So, if you thought about 10 meters of span, then overhang can be of about 1.5 meters to 3 meters. The voides the module, or the web spaces which is triangular in Figure-17, can be used for mechanical service; such as piping, conduit and ductwork. Non-combustible steel construction may be left exposed at least 20' above the finish floor.

Next, we will see about arrangement of the support systems in Space-Frame structure. There are three types of arrangement:

- Straight Column
- Pyramid Capital
- Tree Column

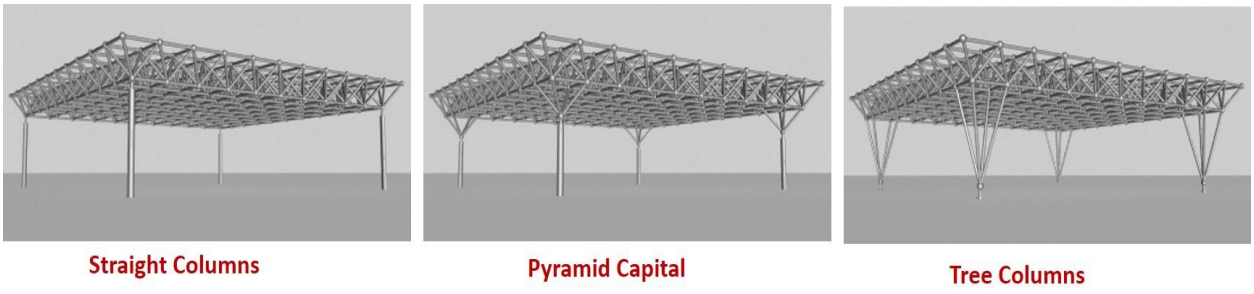

Figure 18 : types of support systems in Space-Frames

Most efficient are Pyramid Capital and Tree Column. Then, why Pyramid Capital or why Tree Columns? Because it is going to increase the influence area that we have already discussed before, that, the how the influence area can be increased by virtue of the geometrical changes of the structure.

So, if you want to reduce the number of supports then you can go for the Pyramid Capital column or maybe the Tree type support system. They allow Space-Frame to be supported by a minimum number of supports and ideal for exhibition halls, manufacturing plants etc. They also reduce the effective span between the supports, the maximum vertical deflection, and member forces. It results in cost-saving - especially for spans over 100 feet**.**

Now these are classification of the Space-Frame as given in Figure-19.

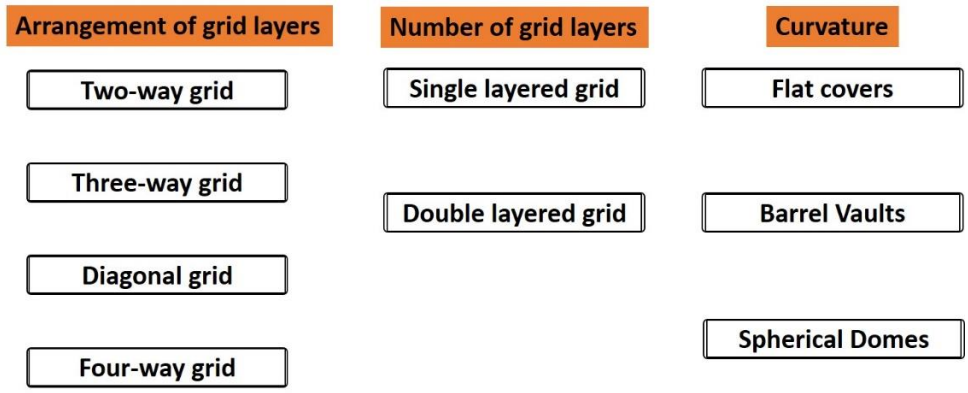

Figure 19 : classification of Space-Frames

If you want to classify; then there are three classifications. One is from the arrangement or the grid layer point of view, next is on the number of the grid layers point of view and the third one is on curvature point of view.

Then under arrangement of grid layers, it is two-way, three-way, diagonal and four-way grids. Then based on number of grid layers it is single layered and the double layered grid. Next, based on curvature, it can be flat covers, barrel vaults and spherical domes.

So those are the some of the examples or the figures of the grid layer arrangements shown in Figure-20.

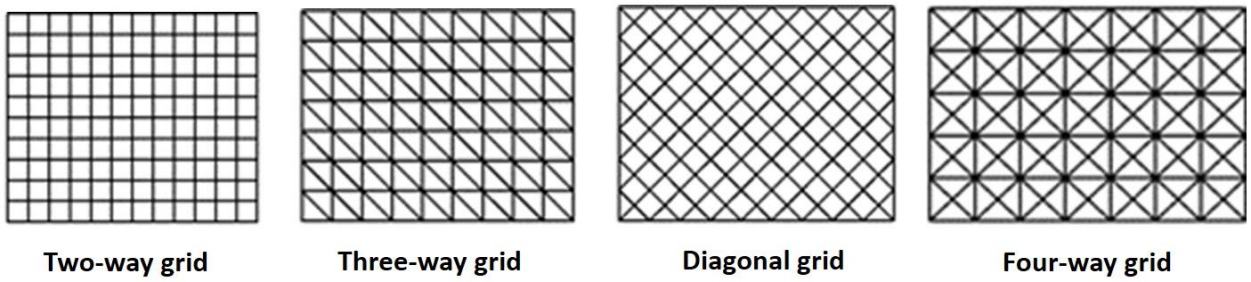

Figure 20 : arrangement of grid layers in Space-Frames

The two-way grid is very much orthogonal, 90 degree to each other; and three-way grid will be with an additional inclined layer to two-way grid. Hence, instead of squares you divide your modules into triangles. The diagonal grid is of two layers only, but they are intersecting at 45º angle. In four-way grid the layers are compact with introduction of a greater number of diagonal members.

Then based on number of grid layer; it is single layered grid and the double layered grid. Single layered grid is not that much common, but double layered grid system is widely used. Sometimes we may go with the triple layered grid systems also.

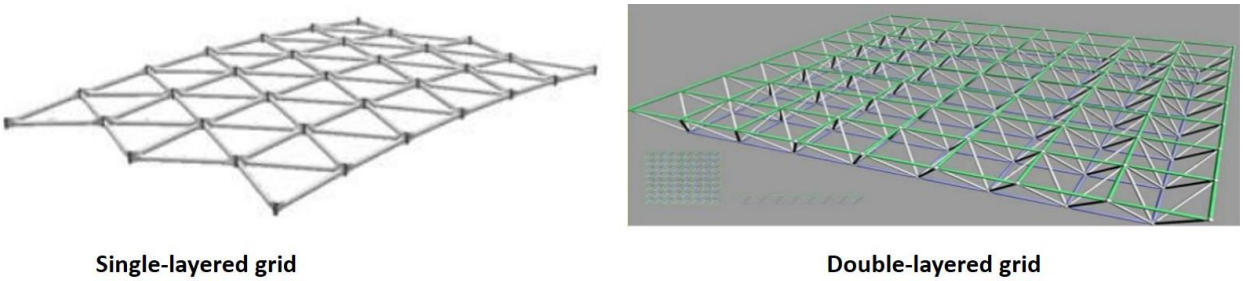

Figure 21 : single layered and double layered grid system

Then depending on its curvature there are three types. First one is the flat covers, which is straight, with no curvature. The next is Barrel Vault kind of fitting; and there may be a two sides curvature like a dome shape. Refer Figure-22.

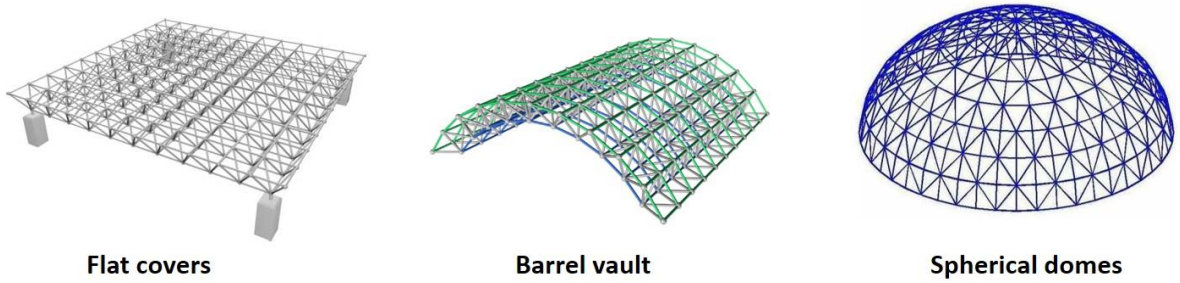

Figure 22 : flat covers, barrel vault and spherical dome shaped Space-Frame

Now, if we see the advantages of Space-Frame then we can say that:

- It is of very light weight.
- It is very elegant & economical.
- It carries load by three-dimensional action, so members are thin and slick.
- It has high inherent stiffness; due to the geometry of unit modules.
- It is easy to construct.
- It saves construction time & cost.
- Services (such as lighting and air conditioning) can be integrated easily with space frames.

- Offers the architects an unrestricted freedom in locating supports and planning the subdivision of the covered spaces.

The Space-Frame structures have well applicability in seismic zones. This one of the structural systems that you can think of in seismic zones; because one of the things is that, it is made of steel and aluminium which are highly ductile and it has a very good inherent property of the stiffness. So, these two are very important criteria for the earthquake resistant structure.

Next is the joints. If you go with these threaded joints or may bolted joints, then these joints can act as an energy-absorbing component for the structure. Since the aluminium is lighter than the steel it is better to go with aluminium. Because if you go the aluminium Space-Frame then the total amount of load, that means the dead load will be less and hence the total amount of earthquake load will also decrease. Because the earthquake load is the type of load that comes from the overall mass of the building. It is inertial load, so if you can reduce the total dead load of the building then amount of earthquake load will also be less. So those are the positive points for Space-Frames that can be used in the in the Seismic zones.

There are enormous examples of Space-frame structures. Here I have shown you a very few. The first one is Dr. MGR Central Railway Station Chennai. If you have been there, then you must have seen the Space-Frame, the tubular Space-Frame and that is of Two-layered. It is not flat; it is a barrel vault kind of a Space-Frame. Refer Figure-23.

Figure 23 : Dr. MGR Central Railway Station Chennai

The next is Hall of Nations, New Delhi. This building is no more; because this has been demolished. This was designed by Raj Rewal in Pragati Maidan, New Delhi. This was one of the wonderful examples of concrete Space-Frame structures. It is shown in Figure-24. If you see it carefully, you will notice that the overall building is with 3D massing of Space-Frame Structures. There are inclined ribs and inclined members, which and all together it creating an attractive and extraordinary effect.

Figure 24 : Hall of Nations, Pragati Maidan, new Delhi

There is another example from Pragati Maidan, New Delhi. There are other halls also, those are the curvilinear spaces. This is a dome shaped structure.

Figure 25 : dome shaped Space-Frame structure, Hall No. 18, Pragati Maidan, New Delhi

This is another important example with single-layered grid; which is not so common in Space-Frames. Because there are minimum of two layers or commonly Space-frames are with at least double-layered grid.

This is another example in Figure-26. This is a park in Abu Dhabi, which is a very modern or contemporary type of construction. I have put this photograph to show you that how less is the number of columns in it. It is a huge area with roads, there are bridges, greeneries, trees and open spaces. But it is covered with a roof, with Space-frames. This is almost equal to the size of 28 soccer fields or half of the Vatican City.

This is designed with minimum number of columns, because if we provide dense or congested columns then this total the sense of beauty, the sense of openness will be destroyed. So, you need to have very less amount of supportive column and there are very less number of columns in it. In the Figure-26, you can see there are only 3 vertical supports, but definitely there are there are some other supports at the central part of the area, which area merged with the Space-Frames on top. Hence, this gives you a clear indication that huge areas can be covered by the Space-Frames with very nominal amount of vertical supports.

The references which I have taken for this lecture and for this week's is lectures are:

- **Structure as Architecture** by Andrew W. Charleson, Elsevier Publication
- **Basic Structures for Engineers and Architects** by Philip Garrison, Blackwell Publisher
- **Structure and Architecture** by Meta Angus J. Macdonald, Elsevier Publication
- **Examples of Structural Analysis** by William M.C. McKenzie
- **Engineering Mechanics** by Timishenko and Young McGraw-Hill Publication

- **Strength of Materials** By B.C. Punmia, Ashok K.Jain & Arun K.Jain Laxmi Publication
- **Understanding Structures:** ***An Introduction to Structural Analysis*** by Meta A. Sozen & T. Ichinose, CRC Press

In conclusion I must say that, the Space-Frames are vector active geometric forms and considered to be a three-dimensional type of Truss system. It is generated by the links and the nodes. It is widely applicable for long span structures like airports, exhibition halls, and stadiums.

In the next week we will go to “Arch, Shell and Dome” which is another important type of structural systems.

Thank you very much.